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# PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

APRIL, 1953

## SETTLING RATE OF SUSPENSIONS IN SOLIDS CONTACT UNITS

By A. A. Kalinske, M. ASCE

HYDRAULICS DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

# SETTLING RATE OF SUSPENSIONS IN SOLIDS CONTACT UNITS

By A. A. Kalinske,[1] M. ASCE

Synopsis

The settling characteristics of various suspensions are important factors in the design and operation of water and sewage clarification basins. Accurate knowledge of such characteristics is of special importance in the upflow type of clarification equipment. The settling rates of various slurries, suspensions, and sludges determine the permissible upflow rates in such units, and also the methods and equipment used in concentrating the sludge to be discharged from the units. The purpose of this paper is to present general information on the settling characteristics of various suspensions and to apply these data to the design and operation of water and waste treatment and clarification basins.

## Settling of Suspensions

The settling velocity of a single particle depends on its weight, size, and shape; on the fluid viscosity and density; and on the proximity of the particle to a solid boundary or other particles. The settling velocity ($v$) of individual spherical particles of diameter $D$ when not influenced by boundaries or other particles is given by

$$v = \sqrt{\frac{4\,g\,(\rho_1 - \rho)\,D}{3\,C_d\,\rho}} \qquad (1)$$

in which $g$ is the acceleration of gravity, $\rho_1$ and $\rho$ are the densities of the spheres and the fluid, respectively, and $C_d$ is a drag coefficient which is dependent on the value of the Reynolds number:

$$\mathbf{R} = \frac{v\,D}{\nu} \qquad (2)$$

Note.—Written comments are invited for publication; the last discussion should be submitted by October 1, 1953.

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In Eq. 2, $\nu$ is the coefficient of kinematic viscosity. For values of **R** less than about 1.0 the so-called Stokes law holds, in which case $C_d = 24/\mathbf{R}$. Over the entire range, values of $C_d$ are as follows:

| Reynolds Number **R** | Drag Coefficient ($C_d$) |
|---|---|
| 0.001 to 2.0 | $24/\mathbf{R}$ |
| 2 to 500 | $18.5/\mathbf{R}^{0.6}$ |
| 500 to 200,000 | 0.44 |

The values of $C_d$ are usually plotted against **R** and such plottings are given in most textbooks on fluid mechanics. Values of $C_d$ for particles of other than spherical shape are always higher than those for spheres. From such a plotting the value of $v$ can be computed from Eq. 1 by trial and error. In Fig. 1 a more

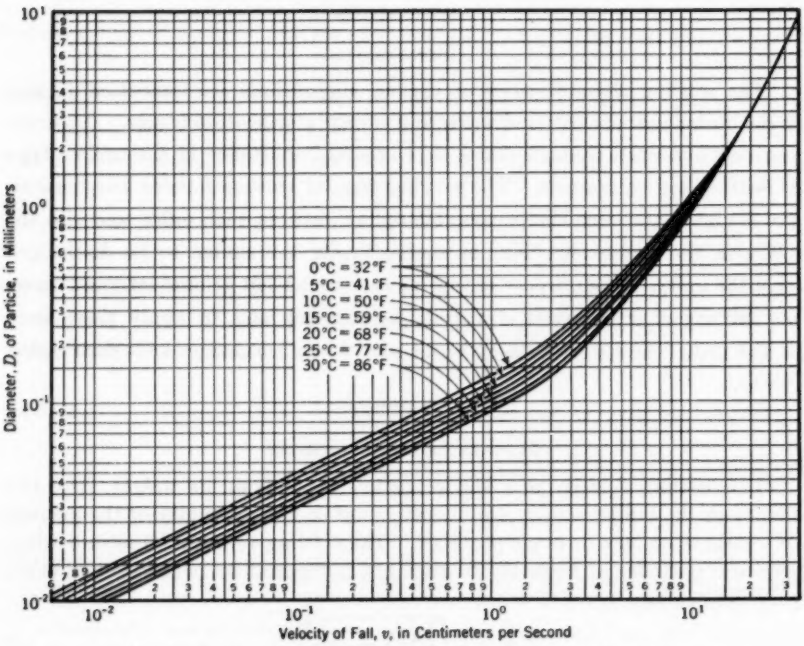


FIG. 1.—SETTLING VELOCITY OF VARIOUS SIZED SPHERICAL PARTICLES

convenient plotting is given from which the settling velocity of spherical particles, having a specific gravity of 2.65 (Silica), can be determined directly.

Suspensions of various concentrations of discrete particles settle at a slower rate than the individual particles. The rate decreases as the concentration increases, in accordance with the phenomenon of "hindered settling"—which begins when the settled solids of a suspension occupy more than about 1% of the original volume of the mixture. By weight this will equal about 1,000 ppm or more of silt and calcium carbonate particles, but will be very much

less for such materials as iron, aluminum, magnesium hydroxide floc, or sewage solids. The settling characteristics of a typical suspension are shown in Fig. 2 in which the height of the suspension is plotted against time. There is an initial period in which the rate of subsidence is at a constant rate, after which the rate decreases. This latter phase is referred to as the "falling rate" period or sludge thickening and compaction period. The settling velocity during the initial "constant-rate" period is of particular importance in connection with the design of clarifiers used for the gravity separation of solids in water and sewage treatment plants.

Experimental data on the settling of suspensions such as are present in water and sewage plants are quite meager. Some experiments have been made on certain suspensions of importance in chemical processes.[2,3] Some measurements obtained by L. T. Work and A. S. Kohler[2] on the settling rate of alumina and calcium carbonate suspensions are shown in Fig. 3. The

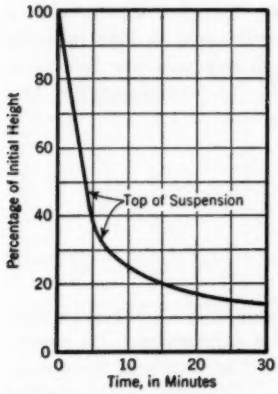


FIG. 2.—SETTLING OF A TYPICAL SUSPENSION

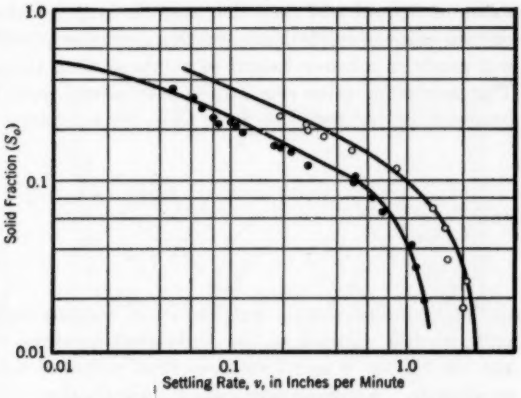


FIG. 3.—RELATION OF SETTLING RATE TO THICKNESS OF SUSPENSION

settling rate during the initial constant-rate period is plotted against the so-called "solid fraction" $S_o$ which is the ratio of final settled volume of solids to the initial volume of the suspension. At low concentrations the settling rate approaches that of the individual particles, and at high concentrations the settling velocity decreases very sharply. The relation appears to undergo a distinct change at values of $S_o$ of about 15%. Above this concentration the decrease in settling velocity is very rapid. There is no reason to believe that other types of suspensions do not follow this same general law. For values of $S_o$ as large as about 15% an empirical, equation that fits the data quite well is

$$V = v - k S_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which $V$ is the initial constant-rate period settling velocity, $v$ is the settling velocity of individual particles, and $k$ is a constant depending on the type of

[2] "Sedimentation of Suspensions," by L. T. Work and A. S. Kohler, *Industrial and Engineering Chemistry*, Vol. 32, 1940, p. 1329.

[3] "Rate of Settling of Suspensions," by H. H. Steinour, *ibid.*, Vol. 36, 1944, p. 618.

suspension. The "solid fraction" is a function of the solids concentration by weight ($C$) and a relation can be expressed as

$$S_o = f\,C\,p \quad \ldots\ldots (4)$$

in which $f$ is a constant dependent on particle size and shape, and $p$, for most practical purposes, is close enough to unity. In computations involving the removal of solids from liquids by gravity settling, it is important to know the weight rate, $q$, of the settling of a suspension. Expressing this in pounds per square foot per unit time, $q$ is equal to the product $V\,C$. From Eqs. 3 and 4 this rate can be written as

$$q = \frac{S_o}{f}(v - k\,S_o) \quad \ldots\ldots (5)$$

It is apparent from Eq. 5 that $q$ will reach a certain maximum for some value of $S_o$ and will then decrease for larger values. In other words, after a certain value of solids concentration is reached, further increase in concentration will result in a lower weight of solids settling through any area per unit time. The maximum value of $q$ can be determined from Eq. 5 by differentiation and by equating the result to zero; thus, for maximum $q$,

$$S_o = \frac{v}{2\,k} \quad \ldots\ldots (6)$$

and

$$q = \frac{v^2}{4\,k\,f} \quad \ldots\ldots (7)$$

Thus, the maximum weight rate of settling depends only on the type, size, and free-fall velocity of the individual particles of a suspension. Of course, the use of Eqs. 6 and 7 requires that values of $k$ and $f$ be obtained from measurements. From certain data it appears that, for suspensions and sludges of the type found in water-softening and clarifying processes, $q$ reaches a maximum for values of $S_o$ ranging between 10% and 15%.

## Suspension of Solids in Upward Flow

The settling of suspensions is closely related to the upward flow through suspensions. The settling rate of a given suspension of solids determines the permissible upflow rate that will maintain the suspension at that concentration. Studies of upward flow through suspensions have direct application in the design of the so-called sludge-blanket water-treating units since the water being treated filters up through a suspension of sludge particles. A common engineering application of suspending solids by upward flow is the backwashing of rapid-sand filters.

If water is forced upward through a bed of solid particles at a gradually increasing rate, the following sequence of events occurs: (1) At very low upflow rates the particles remain in position and the water seeps up by ordinary percolation; (2) as the velocity is increased the top layer is first carried into suspension; (3) continued increase in velocity brings more and more material

into suspension; until finally (4) the entire bed is carried into suspension. The concentration of the suspension will depend on the relative magnitudes of the upward velocity and the settling velocity of the particles in suspension. If there is a variation in the particle size (or, more strictly, in the settling velocity of the particles), the heavier particles will remain at the bottom of the suspension column and the finer particles will be carried toward the top of the zone of suspension.

A detailed set of experiments on the upflow through a suspension of graded sand was made by Hunter Rouse,[4] M.ASCE, and the generalized analysis of the data can be applied to any type of suspension. Fig. 4 is a curve that correlates all the data that were obtained. Its generalized equation is

$$C = K\left(1 - \frac{V'}{v}\right)^{3/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The symbol $V'$ is the nominal upward water velocity (that is, the discharge rate divided by the total sectional area), $v$ is the settling velocity of the material, $C$ is the relative concentration, and $K$ is a constant. As stated, the permissible upward velocity approaches the settling velocity of the individual particles as the concentration approaches zero.

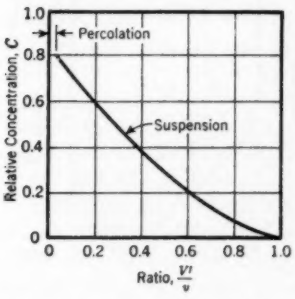


FIG. 4.—VARIATION OF RELATIVE CONCENTRATION OF SUSPENSION WITH RATIO OF UPFLOW VELOCITY TO SETTLING RATE OF PARTICLES

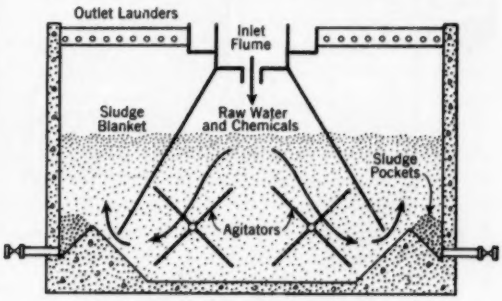


FIG. 5.—DIAGRAM OF A TYPICAL SLUDGE-BLANKET, SOLIDS-LIQUID, SEPARATOR

Analysis of the curve in Fig. 4 leads to several practical implications: For a suspension composed of uniformly settling particles the concentration will be uniform where the upflow is in a cylinder. In an expanding cone the concentration will increase upward. In a cylinder with graded particles the faster settling particles will be at the bottom, and the concentration will be greatest there since $V'/v$ will be low at that point. In an expanding cone the faster settling particles will also remain closer to the bottom but, because $V$ and $v$ both decrease upward, this will tend to cause the ratio $V'/v$ to change more gradually. Thus, the suspension will tend to be of a somewhat more uniform concentration in a cone than in a cylinder.

[4] "Suspension of Sediment in Upward Flow," by Hunter Rouse, *Bulletin No. 26*, Univ. of Iowa Studies in Engineering, Iowa City, Iowa, 1941, p. 14.

The settling rate of a suspension, or of an individual particle, determines the maximum upflow rate that the suspension or particle can stand without being carried up with the moving water. The permissible rise or upflow rate in settling and clarifying units is thus determined by the settling velocity of the particles being removed, either individually or in the form of a suspension. In softening and clarifying units of the "sludge-blanket" type, the settling rate of the sludge suspension itself determines what rise rate the unit can withstand. Increase in the sludge concentration or decrease in water temperature lowers the settling rate, and thus the allowable upflow rate per unit area.

### Liquid Separation from Moving Suspensions

In much of the modern water treatment and sewage clarification equipment, a blanket or pool of sludge or slurry is maintained to accelerate and complete the chemical reactions. Also, such sludge or slurry contact greatly aids in

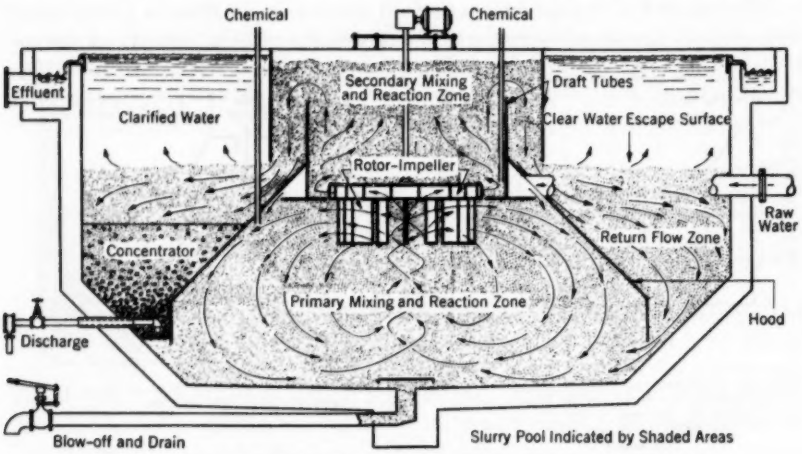


Fig. 6.—Diagram of a Solids-Liquid Separator Using Slurry Circulation

clarification. Such a blanket or pool is maintained by either having the water or waste rise up through the blanket thus keeping the solids in suspension or having some mechanical means for maintaining the solids in suspension independent of the treating rate.

Two types of such solids contact units are shown in Figs. 5 and 6. In Fig. 5 the sludge blanket is maintained by having the "throughput" percolate up the expanding section, thus keeping the solids in suspension. The height of such a sludge blanket will depend on the rise rate as related to the settling rate of the suspension. The characteristics of such a sludge blanket, and the manner in which the solids are distributed in it, can be analyzed from the information presented in Fig. 4.

In the apparatus shown in Fig. 6, a solids or slurry pool is maintained by mechanical circulation of the suspension, and the top level of the pool is independent of the "throughput" rate as long as that rate does not exceed the

settling velocity of the individual particles composing the slurry. This is a noteworthy method of separating a liquid from a slurry since, by the simple expedient of circulating the slurry and discharging it onto a downward moving pool of the same matter, it is possible to separate the liquid from the top of the moving pool. This principle of solids-liquid separation permits keeping a sharp line of demarcation between the solids suspension and the liquid, and this line does not change its level for a wide range of treating rates. The agitation and motion of a slurry keeps it at a fairly uniform composition; and therefore, it behaves similarly to a fluid of heavier density which can withstand considerable motion without mixing with the relatively lighter quiescent liquid above it. This is a well-known phenomenon in the study of so-called "density currents" in fluid mechanics.

## Design Principles

For any given suspension the weight rate of settling (as indicated by Fig. 4) depends on the settling rate of the individual particles and the concentration of the suspension. It is usually advantageous to maintain as thick a slurry as possible; however, if it is too thick, the weight rate of settling may be so decreased that removal of the excess slurry may require large settling areas. Data relating to the settling characteristics of suspensions present in water-softening and clarifying units are important since, with adequate data, proper slurry concentrations and necessary settling areas can be determined accurately.

If the concentration of solids (in pounds per cubic foot) in the incoming raw water or waste, or that produced by the chemical reactions, is $C_r$ and the inflow in cubic feet per minute is $Q$, the total solids to be removed from the unit is $C_r Q$. Since these solids are to be removed by settling, the settling area, $A$, to be provided can be computed thus: The total weight rate of the solids that are settling can be expressed as

$$q = C_s V A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

in which $C_s$ is the concentration of solids in the slurry pool or sludge blanket and $V$ is the subsidence rate of the suspension, in feet per minute. Since this must be equal to the rate at which the solids are coming in or are being produced,

$$A = \frac{(C_r)\, Q}{(C_s)\, v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Eq. 10 indicates that the necessary settling area decreases with an increase in slurry concentration, $C_s$. However, it must be kept in mind that $V$ will tend to decrease as $C_s$ increases. The ratio $C_r/C_s$ in Eq. 10 is significant, since it indicates that the absolute values of $C_r$ and $C_s$ are not so important, but rather their ratio is important in determining the necessary settling area. In general, this ratio will be between 1:3 and 1:10, depending on the type and volume of solids entering the unit. Obviously, it does not vary nearly so much, for instance, as the value of $C_r$. The use of Eq. 10 is thus simplified since it is not necessary to determine the absolute values of the concentrations, $C_r$ and $C_s$, but only their relative values.

It has been demonstrated quite definitely that the basic design criterion for clarification basins is the so-called overflow rate, or rise rate, expressed either in gallons per minute per square foot of basin area, or as a mean vertical rise velocity expressed in feet per minute.[5] This is true for all types of settling basins in which the time factor does not need to be considered as far as chemical or biological reactions are concerned. Of course, this does not mean that the depth of a basin can be ignored completely leaving only the area to be considered. A sufficient depth of clear water must be maintained above the settled solids, or the slurry pool or blanket in upflow units, so that the rising velocity can be distributed properly over the basin area.

The depth of clear liquid that is maintained above the solids in a clarification basin is related to the design of the launder or take-off system. The depth can be less if the launders are so distributed over the basin area as to insure more uniform rising velocity over the basin area. Thus, in upflow basins designed to operate at rise rates of from 1.5 to 2.5 gal per min per sq ft of basin area, a radial or concentric launder system is used in order to provide uniform take-off. Certainly, a rectangular settling basin having only a take-off at the outlet end is not good design since the full area of the basin is not properly utilized for clarification. Of course, such deficiency in take-off can be compensated by an increase in basin depth, but this is not an economical design. In a circular clarifier a peripheral launder is usually provided. An analysis of the hydrodynamics of such a basin indicates that the entire area of such a basin will not be properly utilized unless the depth of clear water to the sludge level is at least equal to one seventh of the basin diameter. If the depth is less than one seventh of the basin diameter, additional take-off, or a better take-off system, should be provided consisting either of a concentric launder set in from the basin wall or a series of radial launders.

## Summary

The proper design and operation of water and sewage clarifying units requires an accurate knowledge of the settling characteristics of various types of solid-liquid mixtures and suspensions. Some basic information is presented and its application to design is indicated. Although available data are extremely scarce, their gradual accumulation will permit a more economical and more scientific design of various types of clarification basins. A careful study of the hydraulic flow patterns in such basins should be made so that a proper and adequate launder or take-off system is provided to utilize the full area of the basin for clarification.

[5] "Sedimentation and the Design of Settling Tanks," by Thomas R. Camp, *Transactions*, ASCE, Vol. 111, 1946, p. 895.

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